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Biomechanical testing of zirconium dioxide osteosynthesis system for Le Fort I advancement osteotomy fixation

Hingsammer, Lukas ; Grillenberger, Markus ; Schagerl, Martin ; Malek, Michael ; Hunger, Stefan

Abstract: The following work is the first evaluating the applicability of 3D printed zirconium dioxide ceramic miniplates and screws to stabilize maxillary segments following a Le-Fort I advancement surgery. Conventionally used titanium and individual fabricated zirconium dioxide miniplates were biomechanically tested and compared under an occlusal load of 120N and 500N using 3D finite element analysis. The overall model consisted of 295,477 elements. Under an occlusal load of 500N a safety factor before plastic deformation respectively crack of 2.13 for zirconium dioxide and 4.51 for titanium miniplates has been calculated. From a biomechanical point of view 3D printed ZrO2 mini-plates and screws are suggested to constitute an appropriate patient specific and metal-free solution for maxillary stabilization after Le Fort I osteotomy.

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Abstract: The following work is the first evaluating the applicability of 3D printed zirconium dioxide ceramic miniplates and screws to stabilize maxillary segments following a Le-Fort I advancement surgery. Conventionally used titanium and individual fabricated zirconium dioxide miniplates were biomechanically tested and compared under an occlusal load of 120 N and 500 N using 3D finite element analysis. The overall model consisted of 295 477 elements. Under an occlusal load of 500 N a safety factor before plastic deformation respectively crack of 2.13 for zirconium dioxide and 4.51 for titanium miniplates has been.
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To whom it may concern,

Clear benefits have been demonstrated for custom-made drill guides combined with individually designed 3D printed patient-specific implants as a reposition and fixation system in Le Fort I osteotomy. However, concerning the used implant material, titanium is the gold standard.

The submitted work is the first evaluating the applicability of a 3D printed zirconium dioxide ceramic osteosynthesis system to stabilize maxillary segments following a Le-Fort I advancement surgery from a biomechanical point of view.

The aim of this study is it to test if individual ZrO_2 mini-plates can stand occlusal forces and might constitute an appropriate metal-free solution for maxillary stabilization after Le Fort I osteotomy using 3D finite element analysis.

Following the results of the study it can be considered as the pioneer work to introduce a new material (ZrO_2) for individually designed 3D printed PSIs in maxillofacial surgery.

Best,

Lukas Hingsammer

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Abstract

The following work is the first evaluating the applicability of 3D printed zirconium dioxide ceramic miniplates and screws to stabilize maxillary segments following a Le-Fort I advancement surgery. Conventionally used titanium and individual fabricated zirconium dioxide miniplates were biomechanically tested and compared under an occlusal load of 120 N and 500 N using 3D finite element analysis. The overall model consisted of 295 477 elements. Under an occlusal load of 500 N a safety factor before plastic deformation respectively crack of 2.13 for zirconium dioxide and 4.51 for titanium miniplates has been.

From a biomechanical point of view 3D printed ZrO_2 mini-plates and screws are suggested to constitute an appropriate patient specific and metal-free solution for maxillary stabilization after Le Fort I osteotomy.

1.1 Introduction:

Le Fort I osteotomy is a well-established surgical technique to correct midfacial deformities presenting the clinical picture of unpleasant esthetic facial contour, facial asymmetries or malocclusion. The surgical treatment includes the separation of the maxilla into free segments to enable its repositioning in the desired, pre-surgically planned position. Regarding the fixation of the adjusted segments, the use of titanium mini-plates and screws is referred as the gold standard (Coskunses et al., 2015; He et al., 2015; Pan and Patil, 2014; Ueki et al., 2006). Typically, the maxillary segment position is planned and primarily reconstructed with articulated dental models made from plaster casts before surgery. As osteotomies are conventionally based on two-dimensional (2D) lateral teleradiographies the precise intraoperative adjustment of the segments using surgical splints is often challenging. To overcome this issue alternative treatment approaches have been introduced. Preoperative virtual surgery planning and rapid prototyping surgical guides have been applied to ensure three-dimensional (3D) planning and separation of the segments in the exact position (He et al., 2015; Hirsch et al., 2009; Li et al., 2013; Mazzoni et al., 2015; Philippe, 2013). However, commercial straight titanium mini-plates, used for fixation still demand contouring to fit segmental maxillary geometry profiles for each individual patient, encountering a risk of inaccurate re-fixation of the segments (He et al., 2015). Furthermore, contouring of the titanium plates often comes along with repeated bending leading to less stress resistance of the plate, increasing the risk of fatigue failure (Philippe, 2013). Custom made prefabricated titanium mini-plates have been investigated and discussed to allow precise control of the surgical procedure and decrease operative time (Mazzoni et al., 2015; Philippe, 2013). Beside titanium plates, poly-L-lactic acid plates and wires have been successfully used to achieve adequate postoperative maxillary stability (Egbert et al., 1995; Ueki et al., 2012). However, metal free solutions are not frequently used, titanium remains the material of choice though its removal is often indicated due to unclear potential bioactive corrosive products (Bianco et al., 1996; Stejskal and Stejskal, 1999; Weingart et al., 1994).

The applicability of a zirconia or zirconium dioxide ceramic (ZrO_2) osteosynthesis system to stabilize maxillary segments following a Le-Fort I advancement surgery has not yet been evaluated. ZrO_2 belongs to the materials with the highest strengths suitable for medical use (von Wilmowsky et al., 2014). The aim of this study is it to test if individual ZrO_2 mini-plates can stand occlusal forces and might constitute an appropriate solution for maxillary stabilization after Le Fort I osteotomy. Postoperative biomechanical behavior and stress distribution on titanium versus ZrO_2 mini-plates after Le Fort I advancement surgery was evaluated using 3D finite element analysis (FEA).

1.2 Materials & Methods:

Using two cast blocks, reflecting the separated segments of the maxilla, advancement of 5 mm and an extrusion of 2 mm was constructed. Individual fabricated ZrO_2 mini-plates and screws (Lithoz®, Vienna, Austria) were applied to stabilize the cast blocks in its position (**figure 1**.). Two straight 3-hole and two angled 4-hole ZrO_2 mini-plates, secured with twelve cylindrical ZrO_2 screws all of which identical to the dimensions of the conventionally available titanium osteosynthesis system Modus 2.0 of Medartis®, Basel, Switzerland were used to achieve a stable fixation. Following this, 3D imaging of the cast blocks using a micro-CT computer tomography (RayScan 250E, Meersburg, Germany) with a voxel size of 65 µm was performed. The resulting DICOM data sets were then transferred to a stereolithography file format using VG Studio MAX 3.0 (Volume Graphics, Heidelberg, Germany). Abaqus CAE 6.12® software was used for creating 3D FE models of the ZrO_2 mini-plates, the cast blocks and the screws. All material properties including cortical bone were assumed to be isotropic, homogeneous and linear elastic. In Model I plates and screws were simulated to be made of conventional pure titanium grade IV and in model II of the existent printed ZrO_2. Material property assumptions regarding Young's modulus and Poisson ratios are listed in **table 1.** Values for ZrO_2 were obtained from Lithoz, Austria and that of pure titanium grade IV as well as that of bone were adopted from the literature (Ataç et al., 2008). Titanium has a pronounced yield behavior whereas ZrO_2 is a brittle material hardly allowing plastic deformation. Therefore, the maximum allowable value for Von Mises stress of ZrO_2 was set according to the yield strength value listed in **table 3.** The number of elements and nodes identical for both models are listed in **table 2.** The plate-to-screw, plate-to-bone and screw-to-bone interface assumed a full bonded condition to exclude micro-movements and to allow stress transfer continuity. The boundary conditions of screw – plate, plate-mono-cortical, and screw-mono-cortical fixation were created as hard contact surface condition.

120 N, 500 N were applied vertically in the molar and premolar region (**figure 2**).

The analysis of the FE models was done by using the Abaqus CAE 6.12® standard/implicit finite element solver. For computing and visualizing the results of the stresses Abaqus CAE 6.12® visualizer was used.

1.3 Results

The 3D-FEA method was used to assess the Von Mises stress as well as the principal maximum stress (P_{max}) on zir ZrO_2 and titanium miniplates in the Le Fort I advancement model. The maximum values of P_{max} and Von Mises stress of the miniplates under 120 N and 500 N vertical loading conditions are shown in **Table 3** for model I (titanium) and II (ZrO_2). All stress values are given in MPa (Newton per millimeter square). A color scale with 13 stress values served to evaluate quantitatively the stress distribution in the plates, screws and the adjacent bone tissue and to provide clear visualization of the stress concentrations.

1.3.1 Von Mises stress values in model I (titanium)

The resulted Von Mises stresses in the titanium miniplates under 500 N loading condition are shown in **figure 3 A**. Maximum Von Mises Stress was 47.87 MPa (120 N) and 183.32 MPa (500 N) respectively.

1.3.2 Von Mises stress values in model II (ZrO_2)

The simulation results indicate that the maximum von Mises stresses for the ZrO_2 miniplates were 47.75 MPa under 120 N and 182.82 MPa under 500 N vertical load.

Figure 3 B illustrates the location of Von Mises stresses of the ZrO_2 miniplates at 500 N.

In both models highest von Mises stresses were determined at the bending of the anterior placed plates. P_{max} for the ZrO_2 plates was 41.09 MPa under weak (120 N) and 72.83 MPa under heavy loads (500 N), respectively. Titanium miniplates resulted in P_{max} levels of 35.18 MPa for 120 N and 60.53 MPa for 500 N loaded models.

The safety factor before plastic deformation at titanium and crack at ZrO_2 occurs was 2.13 for ZrO_2 and 4.51 for titanium under a load of 500 N. When 120 N were applied, calculations revealed a safety factor of 8.16 for ZrO_2 and 17.29 for titanium.

1.4 Discussion

The present study evaluates the applicability of a 3D printed ZrO_2 osteosynthesis system to stabilize maxillary segments following a Le-Fort I advancement surgery. Results reveal a safety factor before plastic deformation respectively crack of 2.13 for ZrO_2 and 4.51 for titanium miniplates under a occlusal load of 500 N. Although no data regarding the bite force after Le Fort I Osteotomy exist, Harada et al. reported mean bite forces of 66.5 N after 2 weeks, 128.8 N after 4 weeks and 301.5 N after 6 months following BSSO surgery. Thus, occlusal loads of 120 N and 500 N were considered to simulate realistic bite forces during and after the bone healing phase of maxillary segments (Harada et al., 2000). Multiple studies report various options, including titanium plates, poly-L-lactic acid plates and wires to achieve satisfactory maxillary stability after single-piece maxillary impactions and/or advancements. All methods provided satisfactory results without any appreciable differences (Egbert et al., 1995; Proffit et al., 1996, 1991; Skoczylas et al., 1988; Ueki et al., 2012). However, the 4-titaniumplate fixation technique constitute the gold standard as compared to the 2-plate fixation technique it significantly reduces stress on healing bones (Ataç et al., 2008). The usage of ZrO_2 devices has not yet been described.

Within the limitations of the study, a safety factor of 2.13 for the ZrO_2 miniplates under excessive occlusal load is considered adequate to ensure an uneventful clinical usage.

It is to be noted that to achieve comparable results, the evaluated ZrO_2 miniplates were fabricated according to the design and dimensions of conventionally available titanium miniplates used for model I without any pre-optimization. Thus, modifications of design and structure to even improve biomechanical behavior especially fracture resistance are clearly seen as new assignments for further investigations.

Titanium has been the gold standard for decades and still remains the material of choice for rigid fixation of freed maxillary segments (Coskunses et al., 2015; Philippe, 2013). Nevertheless, higher concentrations of titanium have been detected within tissue attached to implant surfaces and regional lymph nodes (Bianco et al., 1996; Weingart et al., 1994). These findings raise the question if titanium or its corrosive products have an impact on patients' individual health (Stejskal and Stejskal, 1999; Valentine-Thon and Schiwara, n.d.). Although this issue is not fully elucidated, metal free solutions are not routinely used. Zirconium ceramic has shown excellent biocompatibility and tissue integration (Manicone et al., 2007). Concerning dental implants the low affinity of zirconia to bacteria come along with adequate osseointegration of the material (Al-Radha et al., 2012; von Wilmowsky et al., 2014).

Following the results of this study, ZrO_2 is considered as a potential solution to the raising claim of patients to stable, metal-free and bioinert osteosynthesis material without the routine need of removal (Pan and Patil, 2014; Verweij et al., 2016). Another crucial advantage of a ZrO_2 compared to a titanium osteosynthesis-system is that it does not cause artifacts in the CT or MRI scans (Neumann et al., 2006). This allows proper radiologic assessment of tissue adjacent to the osteosynthesis material and therefore unrestricted detection of diseases is possible (Neumann et al., 2006). Furthermore, patient specific fabricated osteosynthesis and the use of surgical cutting templates is considered to allow a precise positioning of the segments in the virtually planned position (He et al., 2015; Philippe, 2013).

Although clinical trials are missing, the findings of this study assume that individual ZrO_2 osteosynthesis screws and plates are suitable to stabilize freed maxillary segments after Le-Fort I advancement osteotomy. Further, a variety of possible indications for the use of ZrO_2 osteosynthesis material, especially in the field of facial traumatology, is considered. Nevertheless, ZrO_2 has gained increasing popularity as an implant material. Not only the fact that patients assert the claim to best esthetic results and with increasing frequency to metal-free solutions but also the, especially when coated with saliva are reasons for its utilization.

However, increased fracture risk compared to titan implants due to low fracture toughness and stress shielding as a result of a very high elastic modulus (210 GPa) compared to cancellous bone (14.8 GPa) are drawbacks of ceramics (von Wilmowsky et al., 2014).

As this study evaluates the biomechanical behavior of a ZrO_2 osteosynthesis system in the stabilization of the maxillary segments following Le-Fort I osteotomy for the first time, it has to be considered as a thought-provoking impulse to establish metal-free solutions. Beyond a doubt the not realistic simulation of the maxillary segments and the load only applied in one direction do not properly represent the dynamic loading during function. In addition, bone was modeled as linearly elastic and homogenous even though bone in reality is anisotropic and inhomogeneous.

For clinical usage advance computational work is necessary to allow precise fabrication of individual ZrO_2 osteosynthesis parts and the surgical templates to ensure a predictable osteotomy of the segments. Nevertheless, the reported findings indicate a possible scope of patient specific fabricated metal-free osteosynthesis systems.

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Material	Young's modulus (ε) GPa	Poisson ratio (ν)
Cotical bone	14.8	0.3
ZrO_2	210	0.3
Titanium	144	0.33

Table 1. Mechanical properties of cortical bone, ZrO_2 and titanium in finite element analysis.

Part	No. of elements	No. of nodes
Bone	113 739	161 428
4 hole miniplate	5 760	7 884
3 hole miniplate	9 725	13 152
Screw	4 873	3 132
Overall model	295 477	420 939

Table 2. Number of elements and nodes for different structures and the overall model.

Load (N)	Material	P_{max} stress (MPa)	Max. Von Mises stress (MPa)	Yield strength (MPa)	Safety factor before plastic deformation
120	ZrO_2	41.09	47.75	390	8.16
120	Titanium	35.18	47.87	828	17.29
500	ZrO_2	72.83	182.82	390	2.13
500	Titanium	60.53	183.32	828	4.51

Table 3. Maximum Von Mises stress, P_{max} stress, yield strength and safety factor before plastic deformation under differnet loads for titanium and zirconium dioxide miniplates.

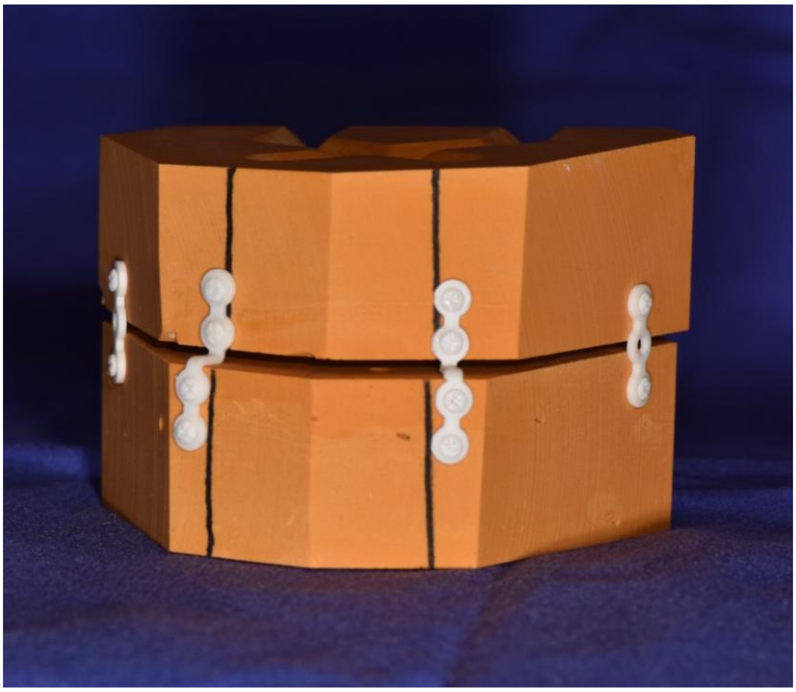


Figure 1. The experimental set up showing the two cast blocks, reflecting the separated maxillary segments stabilized in the desired position using virtually planned and individual fabricated ZrO_2 mini-plates.

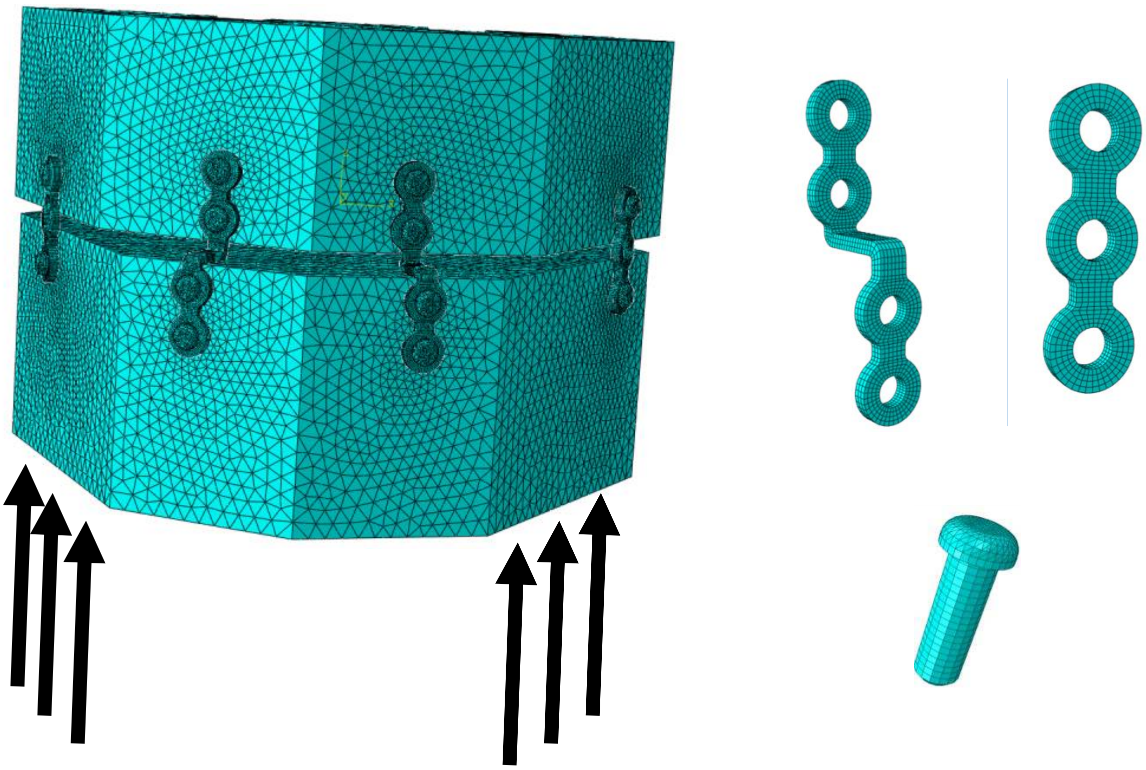
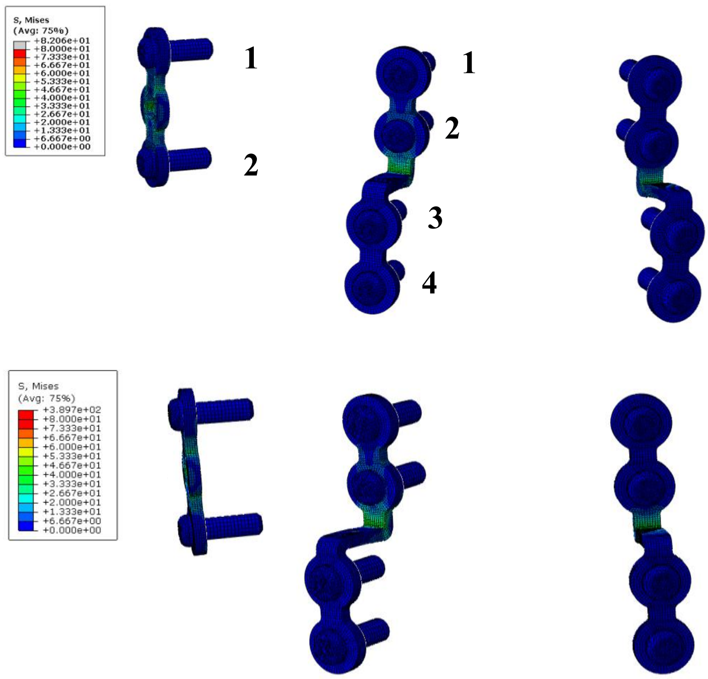


Figure 2. Black arrows on the generated FEA model indicate the direction of loads (120 N, 500 N) simulating occlusal forces.



b

Figure 3. (a) Three-dimensional highest Von Mises stress locations occurring in model I on the titanium screws (numbered from top to bottom) and plates. (b) Three-dimensional highest Von Mises stress locations on ZrO_2 screws and miniplates (model II) under 120 N of loading.

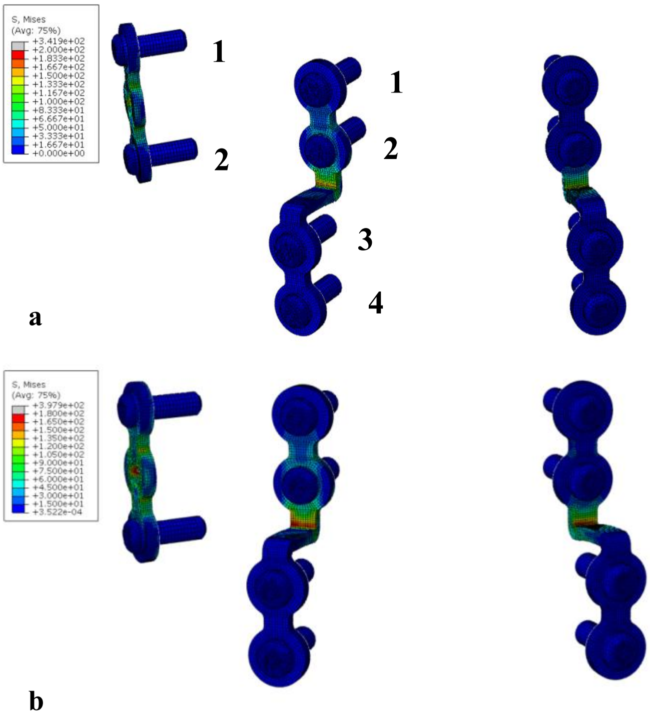


Figure 4. (a) Three-dimensional highest Von Mises stress locations occurring in model I on the titanium screws (numbered from top to bottom) and plates. (b) Three-dimensional highest Von Mises stress locations on ZrO_2 screws and plates (model II) under 500 N of loading.

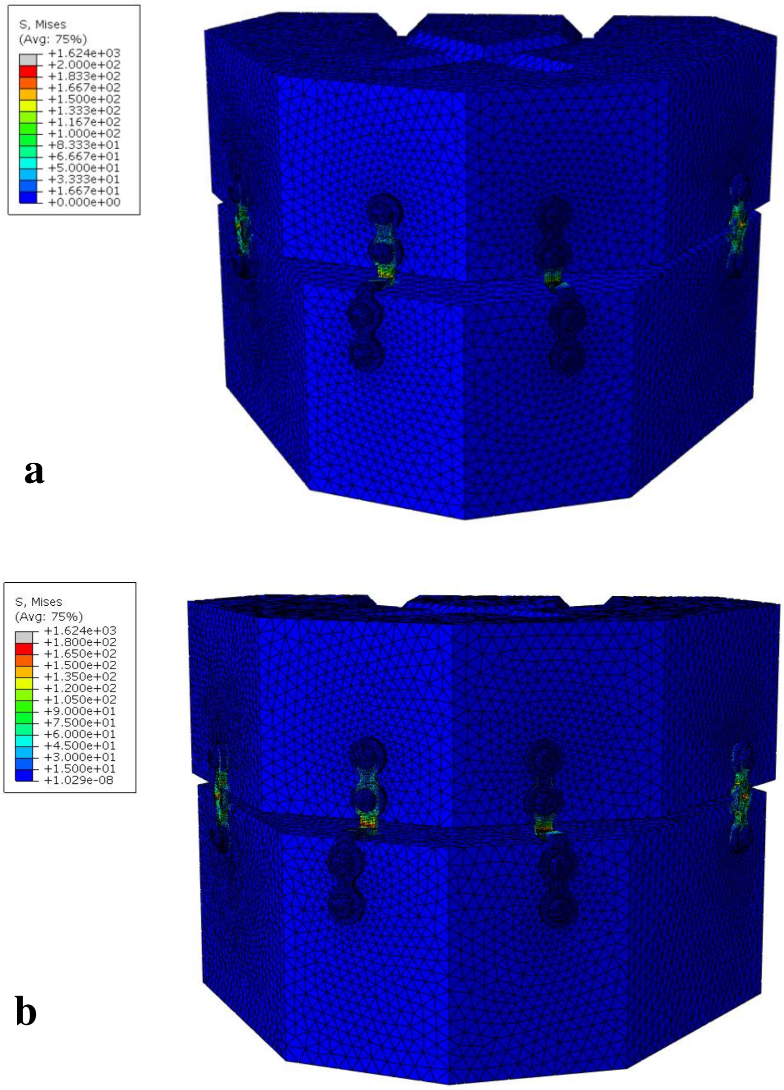


Figure 5. Resulting Von Mises stresses illustrated during 500 N applied load. (a) titanium, (b) ZrO_2.

Graphical abstract